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An overview of energy savings measures for cement industries

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ABSTRACT

Due the advances in the industrial processes, in which the cement industry is a major contributor, energy consumption and greenhouse gas emission has increased significantly. This paper reviews previous studies on energy saving, carbon dioxide emission reductions and the various technologies used to improve the energy efficiency in the cement industry. Energy efficiency measures for raw materials preparation, clinker production, products and feedstock changes, general energy efficiency measures, and finish grinding have been surveyed. It was found that the largest recorded amounts of thermal energy savings, electrical energy savings and emission reductions to date are 3.4 GJ/t, 35 kW h/t and 212.54 kgCO_2/t, respectively.

Contents

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1. Introduction

The industrial sector accounts for 30–70% [1–9] of the total global energy consumption, a considerable part of which can be attributed to the cement industry, as it is instrumental in modernizing the world's cities and infrastructure. A concerted effort is made by the cement industry and related organizations to check the environmental impact of cement production and optimizing both the use of natural resources and the consumption of energy [10]. It is therefore important to pay attention to reduce energy consumption and energy related environmental emissions in both local and global scales [11–15]. In Malaysia, the cement industry consumes about 12% of the total national energy [16]. In Iran, the cement industry consumes about 15% [17]. In comparison, the numbers for California are approximately 1600 GW h per year, 220 MW, and 22 million therms per year, which represents about 5% of the electricity consumption and 1% of the natural gas consumption of the California manufacturing industry, respectively. Thermal energy is used by burning processes, while cement grinding consumes electrical energy [18]. Fig. 1 shows the main energy flow in a typical cement manufacturing process.

1.1. Specific energy consumption

Specific energy consumption is a key indicator of the efficiency of a cement plant in its production of clinker (in MJ/t clinker). A variety of clinker kilns are used that differ in the specific energy consumption and CO_2 emission intensity.

The specific energy consumption varies from about 3.40 GJ/t for the dry process to about 5.29 GJ/t for the wet process. In India, the best reported specific energy consumption is 3.06 GJ/t; while

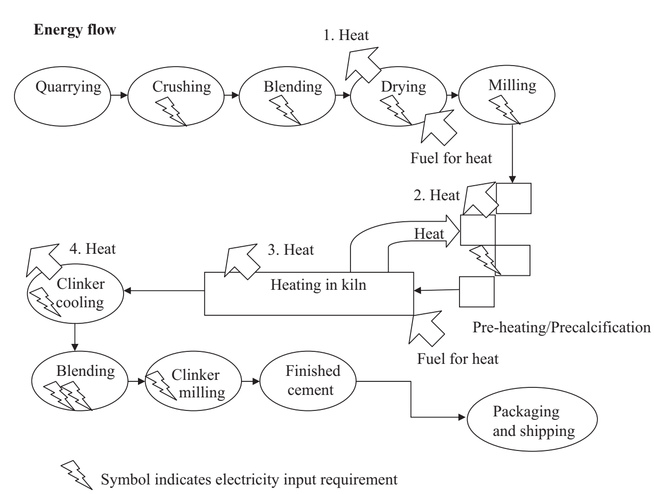

Fig. 1. Main energy flow in a cement production process [19].

in some countries of the world it is lower than 2.95 GJ/t [20–22]. The higher value in India is partly due to the harder raw material and the poor quality of the fuel [23]. The specific energy consumption of the rolls increases linearly with the increase in applied grinding force, although not along with the linear increase in the size reduction [24]. There is a lack of sector-specific studies in Thailand for energy intensive sectors like the cement industry. The 2001 figures for the country show 16% consumption of the entire manufacturing energy consumption by the cement industry [25].

The current global consumption of cement industry is about 1.5 billion tons per annum and is rising at almost 1% per annum. Cement production requires approximately 110 kW h/t of electrical energy, with 40% directed to clinker grinding [26]. Using real auditing, Avami and Sattari [17] investigated technological methods that would reduce the energy consumption, boost productivity and develop the production process of factories in Iran. In Mexico, between 2001 and 2007, there was a 44% growth in energy consumption in the cement industry, with a 6.3% growth rate as is shown in Fig. 2.

Kumar and Madheswaran [28] studied the causal relationship between energy consumption and output growth in the cement industry in India between 1979–1980 and 2004–2005.

Processes like grinding, transport of materials and crushing utilize machine drives and account for the majority of electricity consumption, as is evident in the result of the Manufacturing Energy Consumption Survey (MECS) in 1998 presented in Fig. 3. Process heating, by which clinker is made in large kilns, accounts for about 90% of the natural gas consumption in the cement industry (Fig. 4). Natural gas often acts as a supplemental fuel to coal. A small plant in California that produces white cement uses gas as its primary kiln fuel. The rest of the natural gas consumption is directed to boiler and machine drive end uses [29].

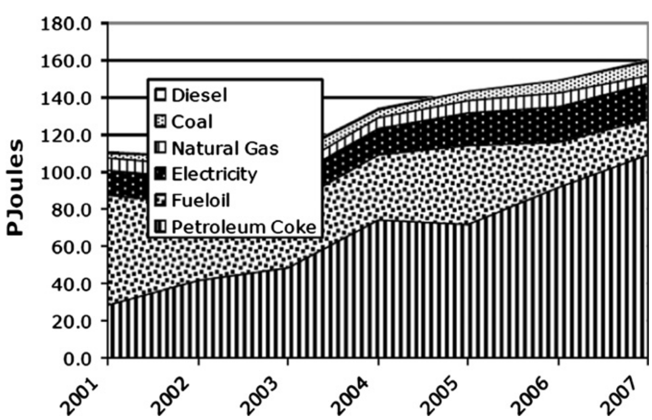

Fig. 2. Energy consumption in the cement industry in Mexico [27].

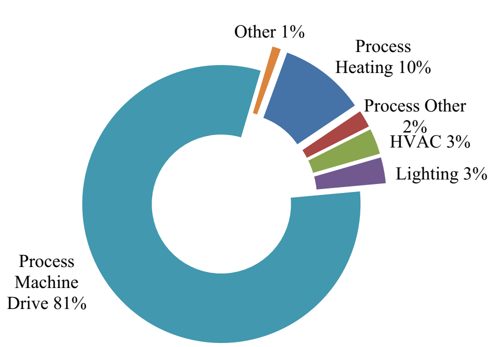

Fig. 3. Cement industry End Use Electricity Consumption [30].

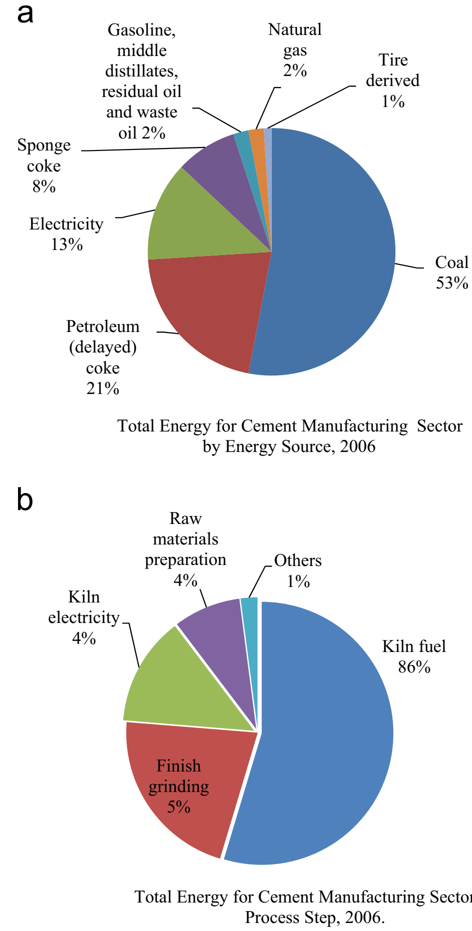

Fig. 4. Total Energy for Cement Manufacturing Sector, 2006 [31].

Fig. 5 illustrates the component ratio of fuel and electric power consumption by the entire Japanese cement industry.

In 2005, the global demand for cement was 2283 million tons and this rose to 2836 million tons by 2010. The demand in China alone constituted 47% of the global demand in 2005 and increased by 250 million tons by 2010. This is a larger increment than the total annual demand of the European Union [33]. In India, there was a rise in cement production from 2.95 million tons in 1950–1951 to 161.66 million tons in 2006–2007 [34]. Table 1 lists the amount of cement production in various countries.

Fig. 6 depicts the average specific thermal and electrical energy consumption for a few selected countries [35].

Table 2 presents the specific thermal energy consumption for various types of clinker manufacturing processes. It is evident that pre-heating with different stages can reduce the energy consumption significantly. The clinker can be pre-heated using waste heat from various sources.

Table 3 presents the energy consumption in different processes of cement manufacturing.

1.2. Cement manufacturing process

Cement manufacturing involves four key processes:

- Dry process: A flowable powder raw meal is obtained after grinding and drying the raw materials, which is passed to either the pre-heater, precalciner kiln or to a long dry kiln.
- Semi-dry process: Water is used to palletize the dry raw meals before passing to a grate pre-heater followed by a kiln, or directly to a long kiln with crosses.

- Semi-wet process: Dewatering of the slurry is performed in the filter process. After extrusion of the filter cake into the pallet, it is passed to a grate pre-heater or straight to a filter cake drier to produce raw material.
- Wet process: A pumpable slurry is obtained by grinding the raw materials, which are generally highly moist. The slurry then goes to a slurry drier or straight to the kiln.

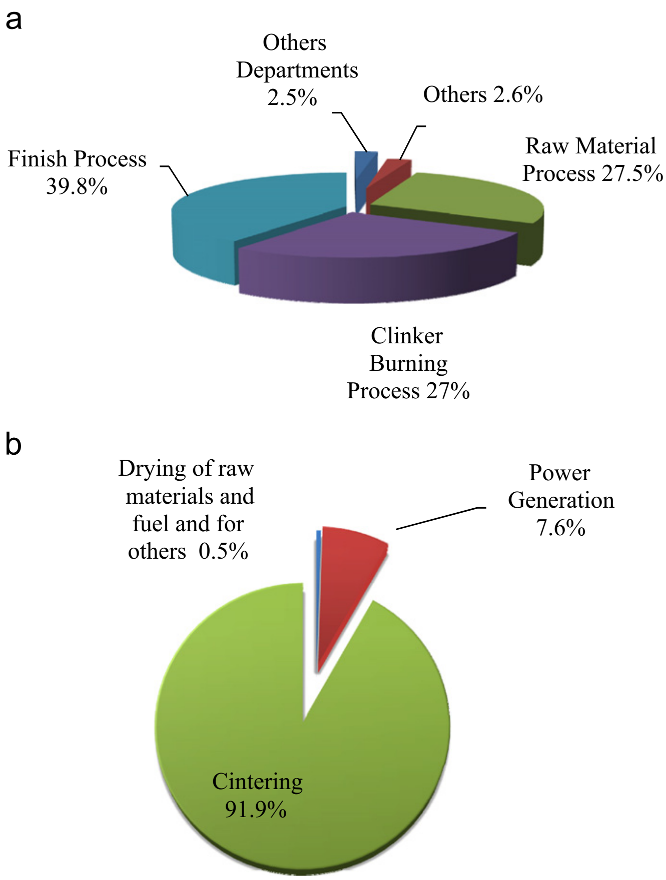

Fig. 5. Component ratio of energy consumption in 1992 [32].

Table 1
Global cement production.

Country	2003	2004	2005	2006	2007	2008	2009
China	865.2	967.8	1 079.6	1 253.5	1 377.8	1 395.3	1 637.1
India	126.7	136.9	146.8	162.0	172.9	186.1	193.1
United States	92.9	97.4	99.4	98.2	95.5	86.5	71.9
Japan	73.8	72.4	72.7	73.2	71.4	67.6	59.6
Turkey	38.1	41.3	45.6	49.0	50.8	53.4	57.6
Iran	30.5	32.2	32.6	35.3	40.0	44.4	56.3
Korea	59.7	55.8	49.1	51.4	54.4	55.1	52.2
Brazil	35.3	36.4	39.2	42.4	47.2	52.3	52.3
Vietnam	24.1	26.2	30.8	32.7	35.7	36.3	48.0
Egypt	32.7	35.5	38.9	39.2	40.1	40.1	46.9
Russian Federation	41.4	46.2	49.5	55.2	59.9	52.3	47.2
Indonesia	34.9	37.9	36.1	38.1	39.9	41.8	39.7
Saudi Arabia	24.1	25.5	26.1	27.0	30.3	37.4	37.8
Thailand	35.6	36.7	37.9	41.3	43.2	39.5	37.7
Mexico	31.8	33.2	36.7	39.2	39.9	38.9	37.1
Italy	43.5	46.1	46.4	47.9	47.5	43.0	36.2
Spain	44.8	46.6	50.3	54.0	54.7	43.1	30.6
Germany	33.6	32.7	31.9	33.6	33.4	33.6	30.4
Pakistan	11.3	14.8	15.8	18.3	26.3	29.2	30.9
Malaysia	18.1	18.1	17.7	20.6	20.5	21.6	21.2
France	19.7	21.0	21.3	22.3	22.3	21.4	18.3

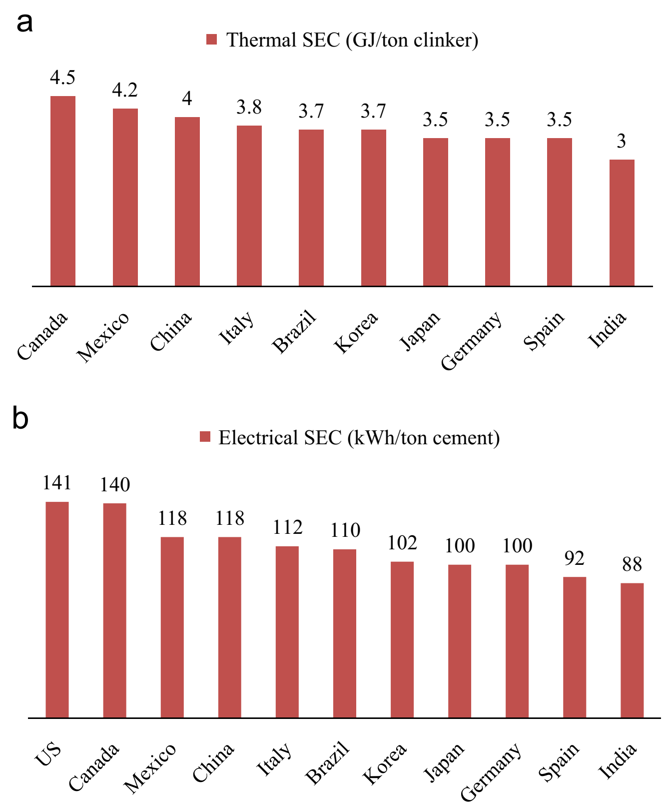

Fig. 6. Electrical and thermal SEC [14].

Table 2
Specific thermal energy consumption in a clinker manufacturing process [36].

Kiln process	Thermal energy consumption (GJ/ton clinker)
Wet process with internals	5.86–6.28
Long dry process with internals	4.60
1-stage cyclone pre-heater	4.18
2-stage cyclone pre-heater	3.77
4-stage cyclone pre-heater	3.55
4-stage cyclone pre-heater plus calciner	3.14
5-stage pre-heater plus calciner plus high efficiency cooler	3.01
6-stage pre-heater plus calciner plus high efficiency cooler	Less than 2.93

Table 3
Energy consumption for each section in the manufacturing of cement [37].

Section	% of total Energy Consumption
Mines and crushing	5
Raw material grinding	24
Raw meal homogenization	6
Kiln	22
Cement mill	38
Material handling and packing	5

The moisture content of raw materials is the key determinant of the process that is employed. Wet processes consume more energy and thus cost more. Generally, only moist raw materials are accessible to plants that use wet or semi-wet processes (Fig. 7).

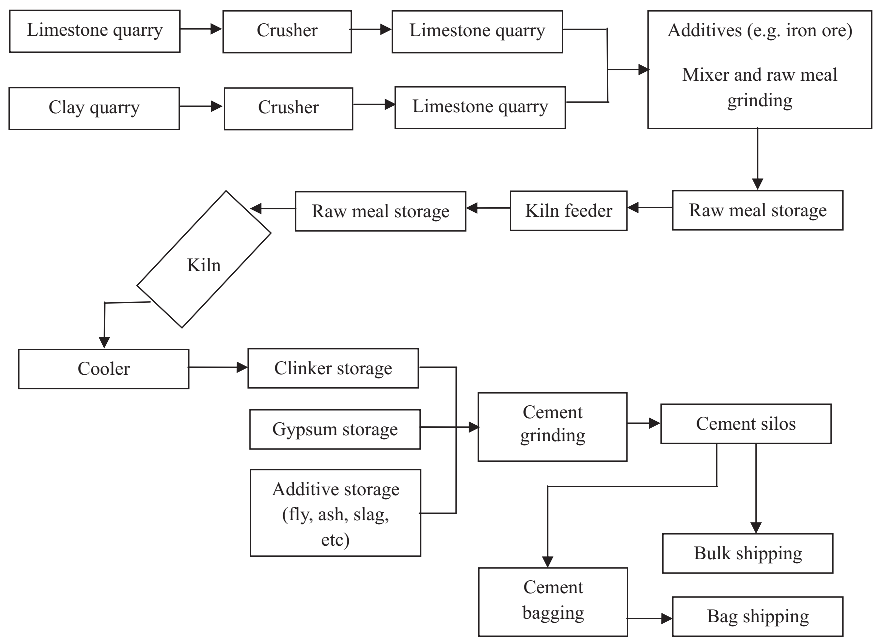

Fig. 7. The manufacturing process (dry SP/PC Kiln) [38].

2. Energy-efficiency measures for raw material preparation ;in cement industry

To improve energy efficiency of raw material preparation in the cement plant, the following options can be used, although not every measure applies to each plant.

2.1. Efficient transport systems for raw materials preparation (dry process)

Kiln dust, kiln feed, finished cement and other powdered materials are moved through the plant using either pneumatic systems or mechanical conveyors, the former using more power than the latter. A study by Dikty et al. [39] examined an energy-efficient pipe conveying system that worked with smaller dedusting equipment at the conveying pipe discharge. Many studies have estimated the thermal and electric energy saving and the emission reduction due to more efficient transportation measures; and the reported figures are 0.02–0.035 GJ/t, 2–3.4 kW h/t, and 0.41–3.22 $kgCO_2$/t, respectively [12,40–45].

2.2. Raw meal blending (homogenizing) systems (dry process)

It is pertinent for raw meal to be homogenized entirely in order to optimize the combustion conditions in the kiln as well as to produce a good quality product. A quality control system in an older dry process was presented by Fujimoto [46], while Holderbank [41] presented it in modern plants. The powdered meal in air-fluidized homogenizing silos is generally agitated using compressed air (using 1.1–1.5 kW h/t raw meal). Documented calculations in thermal and electric energy saving and emission reduction for this measure were as follows: 0.02–0.1 GJ/t, 1–4.3 kW h/t, 0.26–2.73 $kgCO_2$/t, respectively [12,40,41,44–50]. On the other hand, Hendriks et al. [50] showed the electric energy saving ranging from 1.4 to 4 kW h/t.

2.3. Raw meal process control for vertical mills (dry process)

The major issue with vertical roller mills that are currently in use is vibration trips. Manual vibration control becomes problematic when the operation is at high throughput. A trip in the raw mill means an hour's delay till the motor windings cool. The thermal energy saving 0.01–0.016 GJ/t, electric energy saving 1.02–1.7 GJ/t and emission reduction 0.16–1.45 $kgCO_2$/t have been estimated by Hasanbeigi et al. [40], Price et al. [42] and Worrell et al. [44], while Cembureau [48] and Martin and McGarel [51] found an increase of 6% in throughput to correspond to a specific energy consumption reduction of 6% or 0.8–1.0 kW h/t of raw material.

2.4. Use of roller mills (dry process)

Roller mills lead to energy savings while still maintaining good product quality. Using adequate quantities of low grade waste heat from kilns or clinker coolers, the processes of drying and grinding raw materials can be combined [52]. De Hayes [53] reported about a roller mill for raw material grinding installed in Arizona, U.S. in 1998 that improved throughput, raw meal fineness and flexibility and reduced electricity consumption. An estimation of the required investment was performed by Holderbank [41] to be 5.5$/t. The thermal energy saving, electric energy saving and emission reduction was estimated to be 0.08–0.114 GJ/t, 6–11.9 kW h/t, and 1.24–10.45 $kgCO_2$/t, respectively [12,40,42,44,45,48].

2.5. High-efficiency classifiers/separators (dry process)

The use of high-efficiency classifiers or separators is a recent progress in grinding technology. Classifiers separate finely ground particles from coarse particles and can be used in both the raw materials mill and the finish grinding mill. Holderbank [41] and Sussegger [54] developed various concepts of high-efficiency classifiers.

Shapiro and Galperin [55] reviewed the operation principles, features and parameters of modern air classification devices, such as cut size, cleanness and recovery. Also Worrell et al. [12,44] Hasanbeigi et al. [40], Price et al. [42], and Hasanbeigi and Menke [45] estimated the thermal and electric energy savings and the emission reduction to be 0.02–0.057 GJ/t, 3.18–6.3 kW h/t, 0.51–5.23 $kgCO_2$/t. Salzborn and Chin-Fatt [56] and Sussegger [54]

showed a reduction in the use of electricity ranging from 2.8 to 3.7 kW h/t raw material.

2.6. Slurry blending and homogenizing (wet process)

The wet process involves the use of compressed air and rotating stirrers to blend and homogenize the slurry in a batch process. Relatively high energy losses may be incurred due to the use of compressed air because of its poor efficiency and therefore measures to optimize energy use are essential in this system. An efficiently performed mixing uses approximately 0.3–0.5 kW h/t raw material [48]. Worrell et al. [44] found the emission reduction to range from 0.1 to 0.2 kgCO_2/t.

2.7. Wash mills with closed circuit classifier (wet process)

The majority of wet process kilns use tube mills with closed or open circuit classifiers. Cembureau [48] used a tube mill instead of a wash mill and managed to bring down the electricity consumption to 5–7 kW h/t. Emission reduction was estimated to be 0.2–0.3 kgCO_2/t [44].

2.8. Roller mills for fuel preparation

Fuel preparation involves crushing, grinding and drying of coal and is generally done on-site. To avoid dust and fire, coal is shipped in a wet state. Grinding and drying are both accomplished by passing hot gases through the mill. Coal roller mills are available of for throughputs of 5.5–220 t/hour. A number of countries have coal grinding roller mills, including Thailand, China, Japan, Germany, Denmark and Canada. Cembureau [48] experimented vertical roller mills for coal grinding and achieved an energy saving of 7–10 kW h/t coal. Emission reduction was estimated to be 0.2–0.3 kgCO_2/t [44].

3. Energy-efficiency measures for clinker production in cement industry

Below are the available options to improve energy efficiency of clinker production in cement plants. Not every measure applies to each plant.

3.1. Improved refractoriness for clinker making in all kilns

A huge amount of heat loss can occur through a cement kiln shell, particularly in the burning zone. Improved insulating refractories that would cut heat losses were examined by Venkateswaran and Lowitt [52]. Refractories are selected based on the insulating qualities of the brick and the ability to develop and maintain a coating. They protect the steel kiln from heat and mechanical and chemical stress. The material for the refractories is chosen according to the raw materials, operating conditions and fuels. In China, small and medium refractories are produced, although the energy efficiency is lower than those produced by top international companies [57]. The thermal energy saving has been estimated to be 0.12–0.63 GJ/t and the emission reduction estimation has been shown to be 10.3–15.5 kgCO_2/t [44,58,59].

3.2. Energy management and process control systems for clinker making in all kilns

The imperfections in process conditions or process management may cause some heat to be lost from the kiln. Cement plants in different countries use varying systems by different manufacturers. Fuzzy logic and rule-based control strategies feature in most modern systems. Automatic controls should link the processes from mine management to the input of raw materials into the kiln and to the kiln fuel input in order to accomplish production stability [58].

Expert control systems control process conditions by using information from different stages of the process to simulate the optimum human operator, without relying on a modeled process. A good example is the ABB LINKman made in the United Kingdom by Blue Circle Industries and SIRA [60]. The Chinese company Yun Tian offers optimized information technology for energy management and process control [61]. International companies like Siemens and ABB build most of the technology for this purpose, with hardly any being built by domestic companies [57]. Thermal energy savings of 0.1–0.2 GJ/t, electric energy savings of 2.35–5 kW h/t and emission reduction of 2.48–16.61 kgCO_2/t have been found with the implementation of this technology [12,40,42–45,60].

3.3. Adjustable speed drive for kiln fan for clinker making in all kilns

Reduction of power use and of maintenance costs can be accomplished by using adjustable or variable speed drives (ASDs) for the kiln fan. In fact, electricity use can be reduced by 5.5 kW h/t cement [62]. More recent researches show energy savings of 30% [58] and 40% [63]. The thermal energy saving, electric energy saving and emission reduction with this measure have been shown to be 0.05–0.62 GJ/t, 4.95–6.1 kW h/t, and 1.4–6.27 kgCO_2/t, respectively [40,42–44].

3.4. Fan modifications and optimization in all kilns

Friction loss and pressure loss that accompanies with the flow of air through duct can be cut down by expanding the inlet duct of the kiln fan. The minimal capital investments required for these modifications justify the savings, even if they are not great. In their noteworthy study, Menz and Opprecht [64] converted a fan drive from fixed to variable speed.

3.5. Installation or upgrading of a pre-heater to a pre-heater/precalciner kiln for clinker making in rotary kilns

A multi-stage pre-heater kiln may be obtained by addition of a precalciner and an extra pre-heater. The precalciner serves to raise plant capacity and reduce the specific fuel consumption and thermal NO_x emissions, because of the lower combustion temperatures in the precalciner. Normally, the same kiln, foundation and towers are utilized in a modified plant. Coolers are replaced to improve the cooling capacity for bigger volumes of production. Retrofitting of older precalciners can increase energy efficiency and reduce NO_x emissions. While 80–90% of the manufactured precalciner kilns since 2001 were domestic, only 10–20% were imported [65].

Although Chinese technology contributes to only 20–30% of the cost of imported technology, it is less durable and does not cater to kiln sized over 5000 t per day [61]. Fuel consumption reduction of 0.16–3.4 GJ/t clinker has been recorded as a result of reconstruction [66–67]. Thermal energy savings and emission reduction have been seen to be 0.16–0.7 GJ/t and 4.1–40.68 kgCO_2/t, respectively [40,42,44,68].

3.6. Conversion of long dry kilns to pre-heater/precalciner kilns for clinker making in rotary kilns

Long dry kilns can be revamped to be multi-stage pre-heater/precalciner kilns. Thermal energy savings emission reductions with this step have been shown to be 0.4–1.4 GJ/t and 20.46–112.61 kgCO_2/t, respectively [12,40–41,44].

3.7. Dry process upgrade to multi-stage pre-heater kiln for clinker making in rotary kilns

The installation of multi-stage suspension preheating with four or five stages has the potential to lessen heat losses and improve efficiency, compared to the old kilns that contain one or two stages. An important feature of the state-of-the-art cyclone or suspension pre-heaters is the reduced pressure drop and power use in fans. Additionally, they are more efficient in recovering heat.

For this measure, thermal energy savings of 0.73–0.9 GJ/t and emission reduction of 23–72.39 $kgCO_2$/t have been recorded [12,40,41,44]. Duplouy and Trautwein [69] also noted a reduction in specific fuel consumption from 4.1 to 3.6 GJ/t.

3.8. Increasing number of pre-heater stages in rotary kilns

Increasing the number of stages of the pre-heater reduces heat losses and increases kiln efficiency. Adopting this measure can lead to thermal energy savings of 0.08–0.111 GJ/t and emission reduction of 8.44–9.3 $kgCO_2$/t [40,42,43,70].

3.9. Conversion to reciprocating grate cooler for clinker making in rotary kiln

The cooling of clinker can be accomplished by means of four kinds of coolers:

(1) Reciprocating grate coolers
(2) Planetary
(3) Rotary
(4) Shaft

Most modern kilns use the grate cooler, which has a large capacity and efficient heat recovery. Vleuten [71] calculated the savings to be greater than 8% of the kiln fuel consumption, whereas Bump [72] noted 3% reduction in specific fuel consumption. On the other hand, Hasanbeigi et al. [40] and Worrell et al. [12,44] estimated the thermal energy saving and emission reduction to be 0.19–0.3 GJ/t and 6.3–20.46 $kgCO_2$/t, respectively.

3.10. Kiln combustion system improvements

The efficiency of a kiln can compromise due to improperly adjusted firing in fuel combustion systems, inadequate fuel burnout with high CO formation and combustion with excess air [52]. Lowes and Bezant [59] discuss important advances in combustion technology that address these issues.

3.10.1. For clinker making in rotary kilns

Gas burners or gas/coal dual fuel in rotary kilns can also benefit from the recent advancements such as the Gyro-Therm technology that is credited to the University of Adelaide, Australia. Contaminants in popular alternative fuels do not influence the quality of Portland cement and the air emissions from the kiln, even with a 30% fuel supplement [73–75]. Venkateswaran and Lowitt [52], CADDET [76] and Videgar et al. [77] demonstrated the fuel consumption to be between 2 and 10%. The thermal energy savings and emission reduction for this step have been seen to be 0.1–0.24 GJ/t and 2.6–24.13 $kgCO_2$/t [12,40,44].

3.10.2. For clinker making in vertical shaft kilns

Insufficient blower capability and leakage can lead to an inadequate air supply. The quality of raw material pellets should improve and the kiln operation should be accurate if the air distribution is to be enhanced. Measures such as automation of feeding and discharging have modernized vertical shaft kilns, while the older ones are still manually operated [78].

3.11. Indirect firing for clinker making in rotary kilns

Indirect firing is a common feature of modern cement plants, in which neither primary air nor coal is passed to the kiln directly [79]. The primary air supply being decoupled from the coal mill in multi-channel designs, only 7–12% of stoichiometric air is used for primary air [80]. For optimum operation, it is important to adjust the input conditions of the multi-channel burner according to secondary air and kiln aerodynamics [79]. Energy savings of 0.015–0.22 GJ/t and emission reduction of 0.39–0.57 $kgCO_2$/t that come about with adopting this measure were calculated by Worrell et al. [44].

3.12. Optimize heat recovery/upgrade clinker cooler for clinker making in rotary kilns

Clinker coolers come in various designs, the most common being the reciprocating grate, planetary and traveling type. Modern coolers are the reciprocating grate type, which use electric fans and excess air and are well-matched with large-scale kilns up to 10,000 t/d. These coolers reduce the clinker temperature from 1200 °C down to 100 °C. They heat secondary air for kiln combustion and at times the tertiary air for the precalciner, which comes from the highest temperature portion of the excess air [47]. About 5% of the global clinker capacity uses rotary coolers (for plants up to 2200–5000 t/d). Planetary coolers, which are employed for 10% of the global capacity (for plants up to 3300–4400 t/d), do not require combustion air fans or much excess air and therefore exhibit less heat losses [81]. The recorded thermal energy savings for implementing this step have been shown to be 0.05–0.16 GJ/t and the emission reductions have been recorded as 0.8–40.68 $kgCO_2$/t [12,40–45,82,83].

3.13. Seal replacement for clinker making in rotary kilns

Seals at the inlet and outlet of the kiln help to reduce heat losses and false air penetration. However, if they leak the heat requirement of the kiln increases. Therefore, despite the fact that they may last up to 10,000–20,000 h, frequent inspection is necessary. Cui [65] noted the availability of seals in China. Philips [84] recorded a 4% reduction in specific fuel consumption with the implementation of this measure. Also, Worrell et al. [44] estimated the energy saving to be 0.011 GJ/t and the emission reduction to be 0.3 $kgCO_2$/t.

3.14. Low temperature heat recovery for power generation for clinker making in rotary kilns

There are 45 rotary kilns in China that have implemented low temperature heat recovery for power generation [85], although it is yet to find widespread use even in modern large-scale rotary kilns, despite government support [65]. It has been shown to bring about thermal energy savings of 0.25–0.345 GJ/t, electrical energy savings of 20–35 kW h/t and emission reduction 4.6–31.66 $kgCO_2$/t [40,42,44,70,86,87].

3.15. High temperature heat recovery for power generation for clinker making in rotary kilns

The energy from waste gas discharged from the kiln, clinker cooler system and the kiln pre-heater system can be converted into power and has been shown to achieve thermal energy saving of 0.21–0.22 GJ/t, electric energy saving of 17.84–22 kW h/t and emission reduction of 3.68–9.25 $kgCO_2$/t [12,40,44].

3.16. Low pressure drop cyclones for suspension pre-heaters for clinker making in rotary kilns

Cyclones with pre-heating systems are a fundamental part of plants. The power consumption of the kiln exhaust gas fan system can be curtailed by installing newer cyclones in plants with lower pressure losses. Studies about the benefits of this measure showed thermal energy savings of 0.02–0.04 GJ/t, electric energy savings of 0.66–4.4 kW h/t and emission reduction of 0.16–2.67 $kgCO_2$/t [12,40,42,44,45,62,82].

3.17. Efficient kiln drives for clinker making in rotary kilns

Kiln rotation consumes a significant amount of power. Single pinion drives that use air clutches and a synchronous motor are the most efficient kiln drives [88]. It is evident in the thermal energy savings, electrical energy savings and emission reduction values of 0.005–0.006 GJ/t, 0.45–3.9 kW h/t and 0.13–0.9 $kgCO_2$/t, respectively recorded with these drives [40,42,44].

3.18. Replacing vertical shaft kilns with new suspension pre-heater/precalciner kilns for clinker making in vertical shaft kilns

A new suspension pre-heater (NSP) technique was presented by GEI [89] for 1000, 2000 and 4000 t/d. The NSP is suited for medium- or large-scale cement plants that are being either expanded or rebuilt. Smaller cement plants have traditionally used the earthen vertical kiln, but this method should be replaced. For this measure, the energy saving and emission reduction have been documented to be 2.4 GJ/t and 62 $kgCO_2$/t.

4. Cement grinding

Grinding of raw materials, coal and clinker consumes upto 70% of the total electrical energy in the cement industry [90]. Optimizing the grinding process is important to make finer cement products, reduce energy consumption and greenhouse gas emissions. By using Barmac crushers to pre-crush the clinker, the throughput of conventional closed grinding circuits can be increased by 10–20% (Fig. 8). Jankovic et al. [26] discussed the possibility of applying stirred milling technology for fine cement grinding.

Grinding circuit efficiency can be improved in three ways [91]:

1. Maintaining proper material and ball charge level and properly venting the mill.
2. Using a high efficiency separator of adequate size.
3. Utilizing high-pressure grinding rolls.

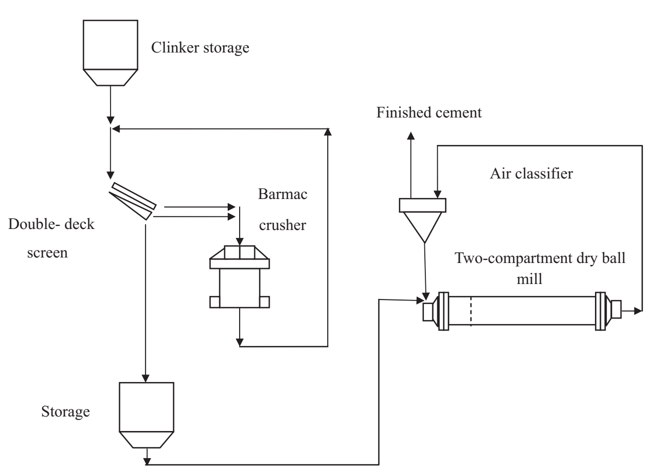

Fig. 8. Simplified cement grinding circuit with pre-crushing stage [26].

4.1. Grinding equipment in the cement industry

It is necessary to reduce the size of raw material before it is fed to the kiln, as it increases the surface area and the reactivity of solids. Also, the clinker size must be lessened before arriving at the finished product. Cement quality is influenced by particle size. Although crushers and cutting machines can be utilized for this task, grinders are increasingly being preferred [92].

5. Energy-efficiency measures for finish grinding in cement industry

This section describes measures to improve energy efficiency for the finish grinding process in cement plants.

5.1. Process control and management in grinding mills for finish grinding

To achieve good quality products, control systems regulate the flow in the mill and classifiers. A study by Tsamatsoulis and Lungoci [93] optimized PID controllers in cement mill installations (CM). Broeck [94] and Goebel and Alexander [95] estimated energy saving to be 2.5–10% and Lauer [96] recorded a 2% reduction in energy consumption with these control systems. The figures for thermal and electric energy savings and emission reduction recorded by Martin and McGarel [51], Hasanbeigi et al. [40], Price et al. [42], Worrell et al. [44] and Albert [97] were 0.03–0.045 GJ/t, 1–4.2 kW h/t, and 0.9-4.11 $kgCO_2$/t, respectively.

5.2. Vertical roller mill for finish grinding

The power consumption of grinding process is influenced primarily by the hardness of raw materials and whether the mill is the ball type or the vertical roller type, with the latter widely replacing the former. The advantages of vertical roller mills (VRM) are that it has 20% lower specific energy consumption than conventional ball mills, they can operate with moisture contents of about 20% in raw materials and have good energy saving potential, due to which they are also being used for clinker grinding. Roller mills are comprised of 2–4 grinding rollers carried on hinged arms riding on a horizontal grinding table and operating with both compression and shearing [48]. The rollers pushed down by springs or hydraulic pressure will grind the raw material. It is followed by drying with hot gas [80].

Savings in thermal energy of 0.2–0.29 GJ/t, in electric energy of 10–25.93 kW h/t and emission reduction of 8.82–26.66 $kgCO_2$/t have been achieved through this measure [40,42–44,98,99].

5.3. High pressure (hydraulic) roller press for finish grinding

HPGRs have been repeatedly shown to be better than conventional ball mills. Beside a 30% energy reduction [100], energy savings up to 10–50% have been documented [101]. Efficiency improvements have also been recorded with high pressure roller presses that can yield up to 3500 bar [102]. The operation cost was also shown to be lower than the alternative technologies [103,104]. A change in the size reduction ratio from 308.2 to 4.4 changed the specific energy consumption of the HPGR from 8.02 to 4.05 kW h/t [105]. The specific and overall energy consumption of different HPGR configurations is summarized in Fig. 9.

Bhatty et al. [80] and Conroy [106] attained 7–30% energy savings with HPGR, while Worrell et al. [12,44], Hasanbeigi et al. [40], Price et al. [42], and Hasanbeigi and Menke [45] estimated

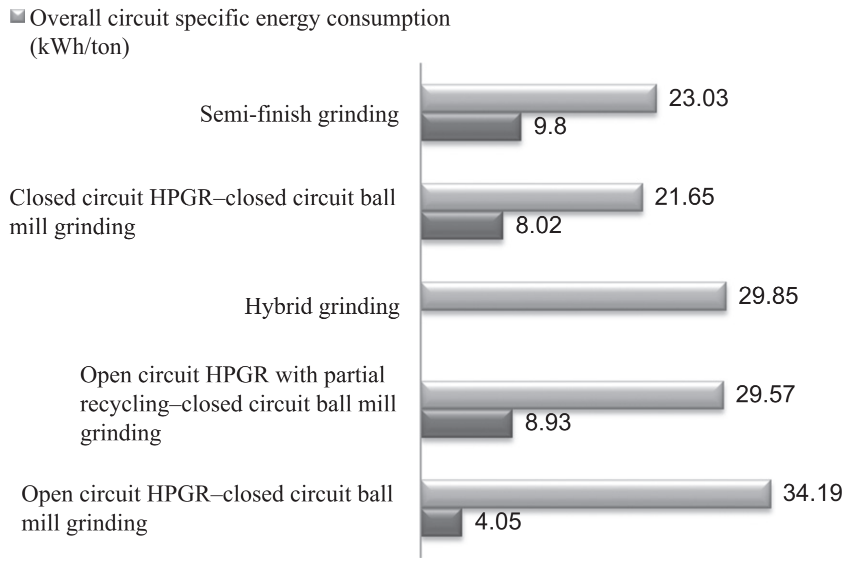

Fig. 9. Specific energy consumption of HPGR circuit with different configurations [105].

the thermal energy savings to be 0.09–0.31 GJ/t, electrical energy savings to be 8–28 kW h/t and emission reduction to be 1.28–25.09 $kgCO_2/t$.

5.4. Horizontal roller mill for finish grinding

The Horomill was first introduced in Italy in 1993 and consisted of a horizontal roller driven within a cylinder [107]. The cylinder movement produces centrifugal forces which form a uniformly distributed layer on the inside of the cylinder. Marchal [108] recorded a pressure of 700–1000 bar when the layer passed the roller. Bhatty et al. [80] found the energy savings to be 35–40% with these mills. Worrell et al. [12] recorded thermal energy savings of 0.3 GJ/t and emission reduction of 4.33 $kgCO_2/t$.

5.5. High efficiency classifiers for finish grinding

Although high efficiency classifiers have been mentioned earlier, additional details related to finish grinding are presented here. High efficiency classifiers have been shown to bring about a reduction of 2.8–3.7 kW h/t in raw materials, save fuel and yield a narrow particle size distribution, increase the grinding mill capacity by up to 15%, produce more uniform particles of raw meal and cement and thus enhance the quality of the product and the clinker [90]. Worrell et al. [44] estimated the investment cost for raw material production to be $2.2/annual t. Improved separators, used in both ball mills and vertical roller mills, stop the product from returning to the mill and thus avoid over-grinding.

A reduction in electricity use of 1.9–7 kW h/t has been recorded as well [41,56,109]. Additionally, 0.04–1.62 GJ/t savings in thermal energy, 7 kW h/t savings in electric energy and 0.4–2.07 $kgCO_2/t$ emission reduction have been shown [12,40,43,44,94].

5.6. Improved grinding media (for ball mills)

Grinding media are normally chosen based on the material wear characteristics. To cut down both wear and energy consumption, the ball charge distribution and surface hardness of grinding media should be increased. Wear resistant mill linings are also effective. The energy saving for this measure was estimated to be 0.02–0.068 GJ/t thermal energy, 1.8–6.1 kW h/t electric energy and 0.29–6.27 $kgCO_2/t$ emission reduction [12,40,42,44,45,52].

6. General energy-efficiency measures in cement industry

6.1. High-efficiency motors and drives

Due to their widespread use, efficient strategies for controlling motors are of the essence. Up to 700 electric motors can be found in a cement plant with various power ratings. A number of functions are performed by motors and drives in a cement plan, including fan movement, grinding, kiln rotation and material transport. Motors can be rewired (which is often preferred to replacement) when necessary [110]. Fujimoto [62], Hendriks et al. [50] and Vleuten [71] found the energy saving to be 3–8% with high-efficiency motors. Thermal and electric energy savings and emission reduction were seen to be 0.03–0.31 GJ/t, 0–25 kW h/t and 0–47 $kgCO_2/t$, respectively [12,40,42,44,45].

6.2. Adjustable or variable speed drives

Variable speed drives (VSD) appear in fans of the coolers, preheaters, kiln and mills among other areas [111]. Better control strategies for motor drives are crucial as they consume the largest portion of power in cement making. Though most motors are fixed speed models, partial or variable load operation is common, especially considering the load variations that often occur in cement plants [112]. Thermal energy saving of 0.09–0.102 GJ/t, electric energy saving of 0.08–9.15 kW h/t and emission reduction of 1–9.41 $kgCO_2/t$ have been accomplished with the use of VSDs [12,42–45].

6.3. High-efficiency fans

As mentioned in the previous subsection, VSDs drive fans in a number of areas in the cement plant. Power use of fans can be optimized by replacing old fans with high efficiency models. UNFCCC [43] found the electric energy saving to range from 0.11 to 0.7 kW h/t.

6.4. Maintenance of compressed air systems

Regular and adequate maintenance is crucial for checking the operating temperatures, moisture level and contamination. It is also important to maintain compression efficiency and control air leakage or pressure changeability, which eventually allows for energy savings.

6.4.1. Reduce leaks in compressed air systems

Leaks can lead to considerable energy loss by deteriorating air tool efficiency and equipment life. Time lost for unplanned maintenance is also a significant drawback. There is even a possibility of superfluous compressor capacity being added. Poorly maintained plants can have a leak rate equal to 20–50% of the total compressed air production capacity, which can be reduced to 10% with proper care [113,114] and can reduce energy consumption by 20% [76,115].

6.4.2. Sizing pipe diameter correctly in compressed air systems

It is important to select the right pipe size in accordance with the compressor system. Insufficient pipe sizing can increase leaks, imposing costs and pressure losses. According to Radgen and Blaustein [115], increasing the pipe diameter cuts 3% of the annual energy consumption.

6.4.3. Heat recovery for water preheating in air compressor systems

Using a heat recovery unit, up to 90% of the heat that is obtained from the converted electrical energy of the air compressor can be recovered and directed to space heating, process heating, water heating, makeup air heating, boiler makeup water preheating, drying, cleaning processes, heat pumps etc [116]. For every 0.05 m^3/s of capacity (at full load), about 50 MJ/h of energy is usable [117]. Using water-cooled compressors, however, the need for an additional stage of heat exchange and the lower temperature of the usable heat dissuades the widespread use of heat recovery. Implementation of this measure can save up to 20% of the energy used in compressed air systems annually for space heating [115].

6.5. Lighting control for plant wide lighting

Occupancy sensors can turn off lights when a room is empty. These sensors have a payback period of about 1 year [118]. Galitsky et al. [119] found that energy up to 10–20% can be saved with the use of occupancy sensors.

6.5.1. Replace mercury lights by metal halide or high pressure sodium lights for plant wide lighting

Replacement of mercury lamps by metal halide can improve energy efficiency, aesthetics and light levels. High pressure sodium lamps can save even more energy where color or lighting levels are less important. Price and Ross [114] found that 50–60% of the total energy can be saved by replacing the mercury lamp with high pressure sodium lamps.

6.5.2. Replace metal halide high-intensity discharge with high-intensity fluorescent lights for plant-wide lighting

Traditional High-intensity discharge (HID) lighting can be substituted by high intensity fluorescent lighting, which contains high-efficiency fluorescent lamps, electronic ballasts and high-efficacy fixtures that optimize energy use.

6.5.3. Replace magnetic ballasts with electronic ballasts for plant wide lighting

Ballasts help to maintain a stable output of light by regulating the electricity used to start a lighting fixture. Older magnetic ballasts can be replaced with newer electronic ballasts to save energy. Energy of 2–25% can be saved by using electronic ballasts [120].

7. Energy-efficiency measures for product and feedstock changes in cement industry

7.1. Changing product and feedstock: Blended cements

Blended cement has been in use globally for several decades. In Europe, 44% of all cement production is done with Portland composite cement, while blast furnace and pozzolanic cement contributes to 12% [48]. With the constantly progressing market and technology, the use of industrial by-products like fly ash, zeolite, limestone and natural minerals has been incorporated in cement production. Chinese cement uses admixtures at an average proportion of 24–26% [121]. The thermal energy saving and reduction in emission with the use of blended cement have been estimated to be 0.009–1.4 GJ/t and 0.3–213.54 $kgCO_2$/t, respectively [12,40,42,44,45,47,58].

7.2. Changing product and feedstock: Use of waste-derived fuels

Traditional commercial fuels can be replaced with waste fuels. For instance, the tire-derived fuels common in North America are obtained by burning 35 million tires annually [122].

Solid, fluid, ground plastic and carpet wastes, besides paint residues and sewage sludge, can also be used [123]. As of 2006, three Chinese plants were burning waste fuels [57]. The Hong Kong Cement Plant buys waste from other provinces [61]. Gielen and Taylor [14] denoted that some kilns in Europe use the alternative fuels such as fossil fuels and the energy saving could be from 3 to 6 GJ/t. On the other hand, Worrell et al. [12,44], Hasanbeigi et al. [40], and CADDET [76] estimated the energy saving up to 1.53 GJ/t and emmission reduction of 12–76.31 $kgCO_2$/t.

7.3. Changing product and feedstock: Limestone Portland cement

Cement obtained by intergrinding ground limestone and clinker lessens the need for clinker-making and calcination. Detwiler and Tennis [124] showed 5% reduction in fuel consumption with power consumption of 3.3 kW h/t and of emission of 5%. A 0.23–0.32 GJ/t thermal energy saving, 2.8–3.3 kW h/t electric energy saving and emission reduction of 8.4–29.86 $kgCO_2$/t has been achieved with this step [40,42,44].

7.4. Changing product and feedstock: Low-alkali cement

Cements with alkali contents that are not more than 50% of those in the market are found in North America [41]. In fact, factors such as customer demands and climate may specifically require low-alkali cements, especially in the U.S. and China, where it is domestically produced [65]. Venting hot gases and particulates from the plant that are loaded with alkali metals reduces the alkali content.

Energy saving and emission reduction occurred with this measure have been calculated to be 0.008–0.5 GJ/t and 4.6–12.1 $kgCO_2$/t, respectively [44,47].

7.5. Changing product and feedstock: Use of steel slag in kiln

Limestone usage was reduced in 1994 when Texas industries in the USA developed an approach that input electric arc furnace slag of the steel industry to the kiln as well. Slag from EAF tri-calcium silicate (C_3S) is easier to transform to free lime than limestone and can replace 1.6 times the weight of limestone. EAFs yield from 0.055 to 0.21 t of slag per ton of steel. This measure is not present in China but is fairly developed internationally [65]. Figures for energy savings and emission reduction for this measure are 0.15–0.19 GJ/t and 4.9–15.28 $kgCO_2$/t [40,44].

8. Conclusions

In this paper, energy saving measures in the cement industry, such as energy-efficiency measures for the preparation of raw materials, production of clinker, and the completion of grinding, general energy efficiency measures, and product and feedstock changes are reviewed. The energy-saving measures studied were shown to be effective ways to improve the energy efficiency and reduce greenhouse gas emissions. The amounts of thermal energy savings, electrical energy savings and emission reductions were seen to vary from 0.05 GJ/t, 0.08 kW h/t and 0.1 $kgCO_2$/t to 3.4 GJ/t, 35 kW h/t and 212.54 $kgCO_2$/t, respectively.

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